Princeton Plasma Physics Laboratory
Ion-Beam-Driven High Energy Density Physics and Heavy Ion Fusion Science*

FY2008 Research Objectives and Fusion Execution Agreements Year-End Progress Report

Task Description: Ion-Beam-Driven High Energy Density Physics and Heavy Ion Fusion Science

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Research Objectives and Milestones for FY 2008

A. Theory and Computations

A.1 Research Objectives for FY 2008

1. Develop leading-order drift compression design concepts for NDCX and its upgrades with time-dependent magnets to compensate for chromatic aberrations of the focal spot due to the coherent velocity tilt for longitudinal compression (June, 2008).

2. Develop optimized analytical and numerical models describing the pulse shaping and neutralized drift compression dynamics for NDCX and its upgrades, with emphasis on emittance growth, collective interactions, effects of solenoidal magnetic field, and coupling between longitudinal and transverse dynamics (September, 2008).

3. Complete development and applications of optimized analytical models for plasma production, and beam steering and manipulation in strong solenoidal and dipole magnetic field configurations for neutralized drift compression (September, 2008).

4. Complete implementation and initial tests of large-scale particle simulations of electron-ion two-stream interactions in bunched beams using optimized numerical models, with electron production mechanisms self-consistently included (September, 2008).

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* Carried out under the auspices of the Heavy Ion Fusion Science - Virtual National Laboratory (HIFS-VNL).

A.2 Fusion Execution Agreement Milestone for FY 2008

5. Complete assessment of the effects of the strong temperature anisotropy instability on finite-length bunched beams (June, 2008).

B Experimental Activities and Feasibility Studies

B.1 Research Objectives for FY 2008

1. Develop plasma and beam diagnostics for installation on the NDCX beamline to provide between-shot information on plasma properties during beam compression experiments, and to measure the spatially resolved ion current density and pulse duration (April, 2008).

B.2 Fusion Execution Agreement Milestone for FY 2008

2. Determine the feasibility of experiments using present facilities and their upgrades to study warm-dense- matter ion-ion plasmas produced from halogen foil targets heated by intense ion beams depositing energy near the dE/dX peak (September, 2008).

Year-End Progress Report – 9/30/08

Research Objectives and Milestones for FY 2008

A. Theory and Computations

A.1 Research Objectives for FY 2008

1. Develop leading-order drift compression design concepts for NDCX and its upgrades with time-dependent magnets to compensate for chromatic aberrations of the focal spot due to the coherent velocity tilt for longitudinal compression (Completed June, 2008).

To compensate for the time-dependant focusing due to a velocity tilt and tilt-core time-dependent defocusing effect, a scheme with two focusing solenoids has been proposed and studied analytically. The optimal configuration giving minimal spot size at the focal plane is found to be a combination of weak and strong solenoids. The weak solenoid provides focusing close to the desired focal plane, and the strong solenoid is positioned near the focal plane at the end of the focusing system, providing a tight focus. The minimum radius of the beam at the focal plane is given by

$$R_{f\,\min} = \frac{R_0 dV_z}{V_z}\sqrt{8\frac{F_2}{F_1}}$$

Here, R_0 is the initial beam radius, dV_z/V_z is relative velocity tilt applied, F_2 is the focal length of the strong solenoid, and $F_1 >> F_2$ is the focal length of the final transport solenoid. Without the strong solenoid, the beam radius at the waist is given by $R_0\, dV_z/V_z$. Therefore, there is an enhancement in the radial compression by the factor $F_1/8F_2$. For example, if $F_1=200$ cm and

$F_2=10$ cm, the enhancement in radial compression due to the combination of strong solenoid and weak solenoid focusing is a factor of 2.5.

In addition, the beam *wobbler concept* is currently being investigated by the Heavy Ion Fusion Science Virtual National Laboratory as an effective beam smoothing technique which enables uniform deposition of beam energy onto an annular region on the target, and is capable of suppressing the Rayleigh-Taylor instability. The wobbler system consists of two sets of electrode plates in the two transverse directions driven by RF voltages. As the beam passes through the electrode plates, the beam centroid is deflected in the transverse direction by the applied electric field. However, different slices of the beam will be accelerated differently because the plates are driven by time-dependent RF voltages (Figure 1).

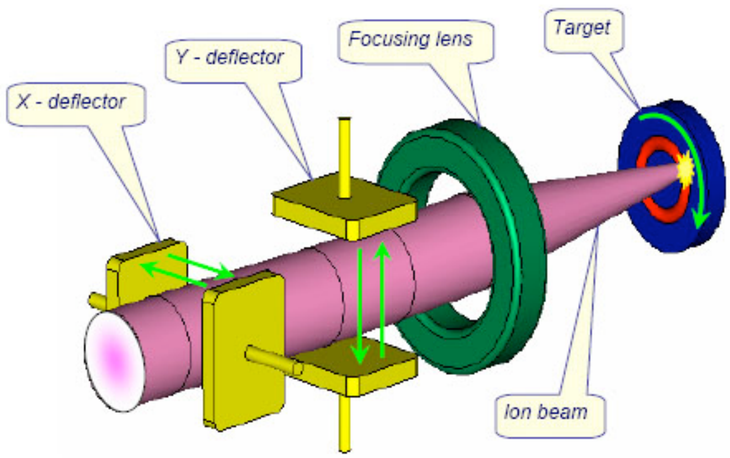

Figure 1. Wobbler and final focusing system

The design goal of the wobbler system is to ensure that different slices are uniformly distributed onto an annular region on the target. The beam will pass through the final focusing magnets after the wobbler plates, to reach a small focal spot size on the target. Therefore, the centroid dynamics, which describe the trajectory of the beam, and the envelope dynamics, which determine the transverse dimensions of the beam, are coupled. Under the auspices of the present contract, we have derived the following set of self-consistent coupled centroid-envelope equations which describe the centroid and envelope dynamics of the beam passing through the wobbler and final focusing system,

$$\frac{d^2}{ds^2}\mu = -\kappa_x(s)\mu - F_x(s),$$
$$\frac{d^2}{ds^2}\nu = -\kappa_y(s)\nu - F_y(s),$$
$$\frac{d^2}{ds^2}a = -\kappa_x(s)a - \frac{\varepsilon_x^2}{4a^3} - \frac{1}{a}\left\langle \frac{\partial\psi}{\partial x}(x-\mu)\right\rangle,$$
$$\frac{d^2}{ds^2}b = -\kappa y(s)b - \frac{\varepsilon_x^2}{4b^3} - \frac{1}{b}\left\langle \frac{\partial\psi}{\partial y}(y-\nu)\right\rangle,$$

where $F_x(s)$ and $F_y(s)$ are the applied external force due to the electrode plates, ψ is the self space-charge potential of the beam, $(\mu,\nu) = (\langle x\rangle,\langle y\rangle)$ is the transverse position of beam centroid, and $\langle\ \rangle$ denotes the average over transverse phase space. The beam envelopes are defined relative to the centroid position as $a = \left\langle (x-\mu)^2 \right\rangle^{1/2}$ and $b = \left\langle (y-\nu)^2 \right\rangle^{1/2}$, and the beam emittances are defined as

$$\varepsilon_x^2 = 4\left[a^2\left\langle (x'-\mu')^2\right\rangle - \langle (x'-\mu')(x-\mu)\rangle^2\right],$$
$$\varepsilon_y^2 = 4\left[b^2\left\langle (y'-\nu')^2\right\rangle - \langle (y'-\nu')(y-\nu)\rangle^2\right].$$

The effects of the first-order non-uniform electric field of the wobbler plates, as well as the applied magnetic focusing field, are included in the focusing coefficients, $\kappa_x(s)$ and $\kappa_y(s)$. If the beam density is uniform in the transverse plane, then it can be shown that the emittances defined above are *exactly* conserved quantities. This set of centroid-envelope equations will form the basis for the design studies of the wobbler and final focusing system for heavy ion beam drivers for applications in high energy density physics and inertial confinement fusion.

2. Develop optimized analytical and numerical models describing the pulse shaping and neutralized drift compression dynamics for NDCX and its upgrades, with emphasis on emittance growth, collective interactions, effects of solenoidal magnetic field, and coupling between longitudinal and transverse dynamics (Completed September, 2008).

To achieve the high focal spot intensities necessary for high energy density physics and heavy ion fusion applications, the ion beam pulse must be compressed transversely by a factor of ten or more before it is focused onto the target. To achieve maximum compression, the space charge of the ion beam is neutralized by propagation of the beam pulse through a dense neutralizing background plasma. If the space charge is fully neutralized by the plasma, the final compression is limited only by the initial temperature of the beam ions and possible collective processes (such as the two-stream and filamentation instabilities) which may prevent full neutralization of the beam space charge. In one scenario, transverse compression of the beam ions is facilitated by using solenoidal focusing magnets. Fields from the magnets can extend to a large distance away from the solenoid into the neutralizing plasma and can change the nature of collective instabilities experienced by the compressing beam when it propagates through the neutralizing background plasma. If $\omega_{ce} > \beta_b \omega_{pe}$, where ω_{ce} is the electron gyrofrequency, ω_{pe} is the electron plasma frequency, and β_b is the ion-beam velocity relative to the speed of light, the helicon waves propagating almost transversely to the beam propagation direction can now be resonantly excited by the beam, drastically changing the way current is being neutralized by the background plasma. Coupling to the helicon waves will also modify the electromagnetic filamentation (Weibel) instability. Under the auspiuces of the present contact, it has been shown that the growth rate is modified compared to the case with weak magnetic field because the electrons are now magnetized, and the instability is between the beam ions and the background plasma ions [E. A. Startsev, R. C. Davidson and M. Dorf, Physics of Plasmas **15**, 062107 (2008)]. The Weibel instability becomes limited to very small propagation angles and long longitudinal wavelengths satisfying $k_{\parallel}^2 = k_{\perp}^2$ and $c^2 k_{\parallel}^2 = \omega_{pb}^2 \omega_{pi}^2 / (\omega_{pb}^2 + \omega_{pi}^2)$, where ω_{pb} and ω_{pi} are the plasma frequencies of the beam ions and the background plasma ions, respectively. For large longitudinal wavenumbers, the instability becomes the low-frequency electrostatic lower-hybrid instability with a growth rate that is $\omega_{ce} / \beta_b \omega_{pe}$ times larger than the growth rate of the Weibel instability.

Because the frequency of the unstable perturbation is a function of wavenumber, an initial perturbation will grow and convect at the same time. The resulting shape of the phase-fronts can change with time and become quite complex. We have studied the asymptotic space-time development of the modified two-stream instability using a WKB analysis. The results of the analysis have shown that the phase-fronts of the unstable perturbation have the somewhat peculiar shape shown in Figure 2, which is qualitatively similar to what is found in numerical simulations using the LSP code (Figure 3).

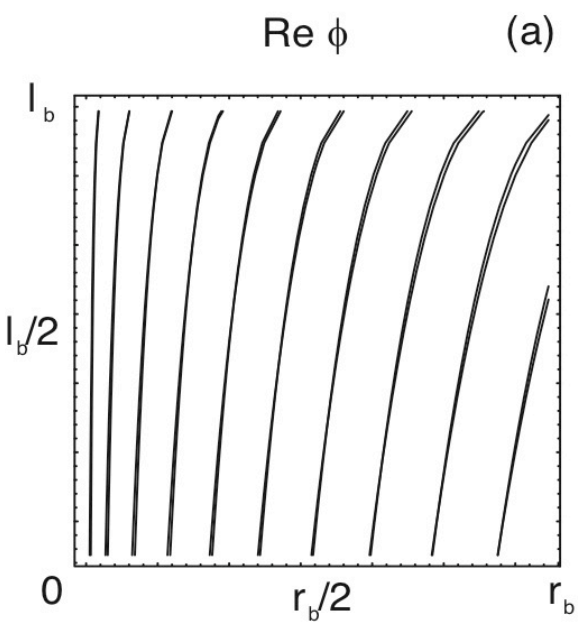

Figure 2. Contour plots of (a) $\mathrm{Re}\phi$ and (b) $\mathrm{Im}\phi$ of the extremal phase ϕ at time $t=(\omega_{pe}/\omega_{pb})l_b/c$ plotted for $n_b/n_e=0.5$, $\beta_b=0.2$, bunch radius $r_b=1.5c/\omega_{pe}$, bunch length $l_b=10r_b$ and $\omega_{ce}/\omega_{pe}=1.4$.

Figure 3 shows color contour plots of the normalized electron density n_e/n_{e0}, including collective excitations, for $n_b/n_e=0.5$, $\beta_b=0.2$, $r_b=1.5c/\omega_{pe}$ and $l_b=10r_b$ and several values of magnetic field strength corresponding to $\omega_{ce}/\omega_{pe}=0,0.7,1.4$. Here, n_{e0} is the ambient electron density. The characteristic shape of the phase-fronts (curves of maximum density) is similar to what is found using an asymptotic analysis of the instability [compare Figure 2(a) and Figure 3].

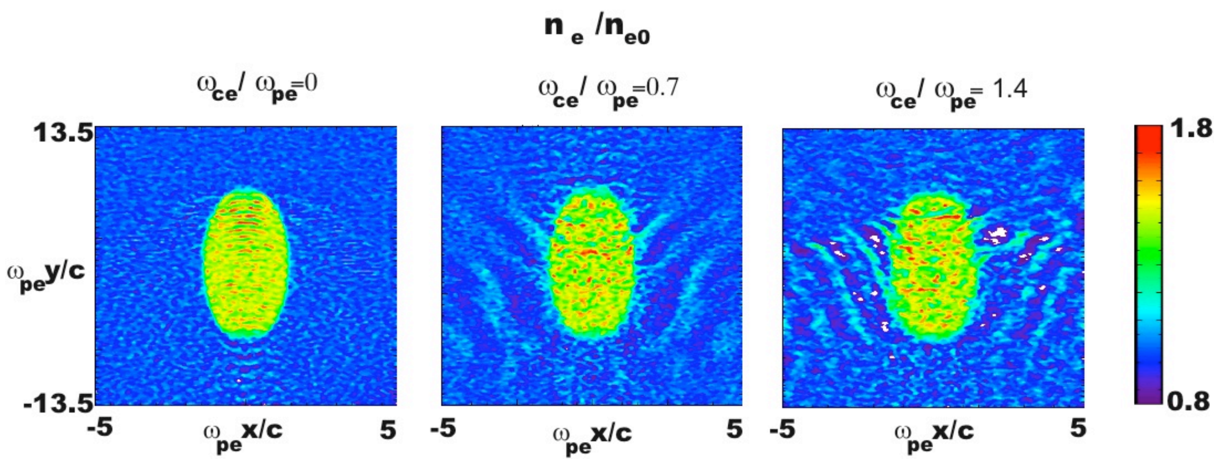

Figure 3. Color plot of the normalized electron density n_e/n_{e0} including collective excitations obtained using LSP simulations of a potassium K^+ ion beam propagating in neutralizing background plasma upward along a solenoidal magnetic field pointing in the y-direction for $n_b/n_e=0.5$, $\beta_b=0.2$, $r_b=1.5c/\omega_{pe}$, $l_b=10r_b$ and several values of magnetic field strength corresponding to $\omega_{ce}/\omega_{pe}=0,0.7,1.4$.

3. Complete development and applications of optimized analytical models for plasma production, and beam steering and manipulation in strong solenoidal and dipole magnetic field configurations for neutralized drift compression (Completed June, 2008).

Space-charge-dominated ion beam pulses for warm dense matter and heavy ion fusion applications must undergo simultaneous transverse and longitudinal compression in order to reach the desired high beam intensities at the target. Longitudinal focusing is achieved by imposing an axial velocity tilt on the beam, and subsequently neutralizing its space-charge and current in a drift region filled with high-density plasma. A strong solenoid (multi-Tesla) near the end of the drift region is included to transversely focus the beam to a submillimeter spot size coincident with the longitudinal focal plane. The neutralization provided by the background plasma is critical in determining the total achievable compression of the beam pulse. Long-time and large-space-scale plasma flow simulations indicate that adequate plasma densities can be provided throughout the drift region for ion beam charge neutralization in near-term focusing experiments in the Neutralized Drift Compression Experiment (NDCX).

The application of a small solenoidal magnetic field can drastically change the self-magnetic and self-electric fields of the beam pulse, thus allowing effective control of the beam transport through the background plasma [I. D. Kaganovich, E. A. Startsev, A. B. Sefkow, and R. C. Davidson, "Charge and Current Neutralization of an Ion-Beam Pulse Propagating in a Background Plasma along a Solenoidal Magnetic Field**"**, Phys. Rev. Lett. **99**, 235002 (2007)]. An analytical model has been developed to describe the self-magnetic field of a finite-length ion-beam pulse propagating in a cold background plasma in a solenoidal magnetic field. The analytical studies show that the solenoidal magnetic field starts to influence the self-electric and self-magnetic fields when $\omega_{ce} > \omega_{pe}\beta_b$, where $\omega_{ce} = eB/mc$ is the electron gyrofrequency, ω_{pe} is the electron plasma frequency, and β_b is the ion-beam velocity relative to the speed of light. Theory predicts that when $\omega_{ce} \sim \omega_{pe}\beta_b$ there is a sizable enhancement of the self-electric and self-magnetic fields due to the dynamo effect [I. D. Kaganovich, E. A. Startsev, A. B. Sefkow, and R. C. Davidson, "Controlling Charge and Current Neutralization of an Ion Beam Pulse in a Background Plasma by Application of a Solenoidal Magnetic Field", submitted for publication (2008)]. This threshold value of the solenoidal magnetic field is relatively small for nonrelativistic beams.

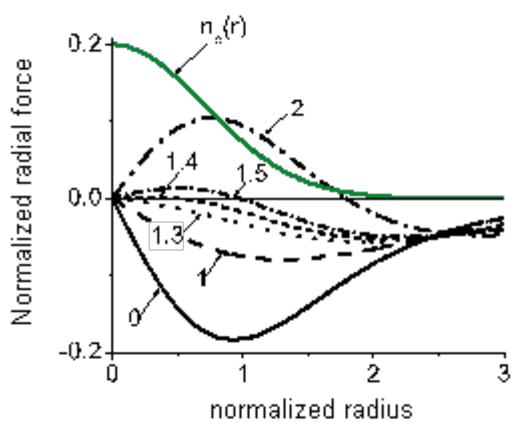

Figure 4. The normalized radial force acting on the beam particles for different values of the parameter $(\omega_{ce}/\omega_{pe}\beta_b)^2$. The green curve shows the Gaussian density profile multiplied by a factor of 0.2 in order to fit the profile into the plot. The beam radius has been chosen to be equal to the skin depth in the figure.

The dynamo effect occurs due to the electron rotation, which twists the applied magnetic field and generates a self-magnetic field that is much larger than in the case with no applied magnetic field. Another effect is the generation of a large radial electric field. Because in steady state the **v × B** force should be balanced by a radial electric field, the electron rotation results in a plasma polarization and produces a much larger self-electric field than in the case with no applied magnetic field. The third unexpected effect is that the joint system consisting of the ion-beam pulse and the background plasma acts as a paramagnetic medium, i.e., the solenoidal magnetic field is enhanced inside of the ion-beam pulse. For larger values of the solenoidal magnetic field, the beam can generate whistler and lower-hybrid waves. In the presence of the solenoidal magnetic field, the radial force acting on the beam ions can change sign from focusing to defocusing, because the radial electric field increases more rapidly than than the magnetic force, as the solenoidal magnetic field increases, as shown in Figure 4.

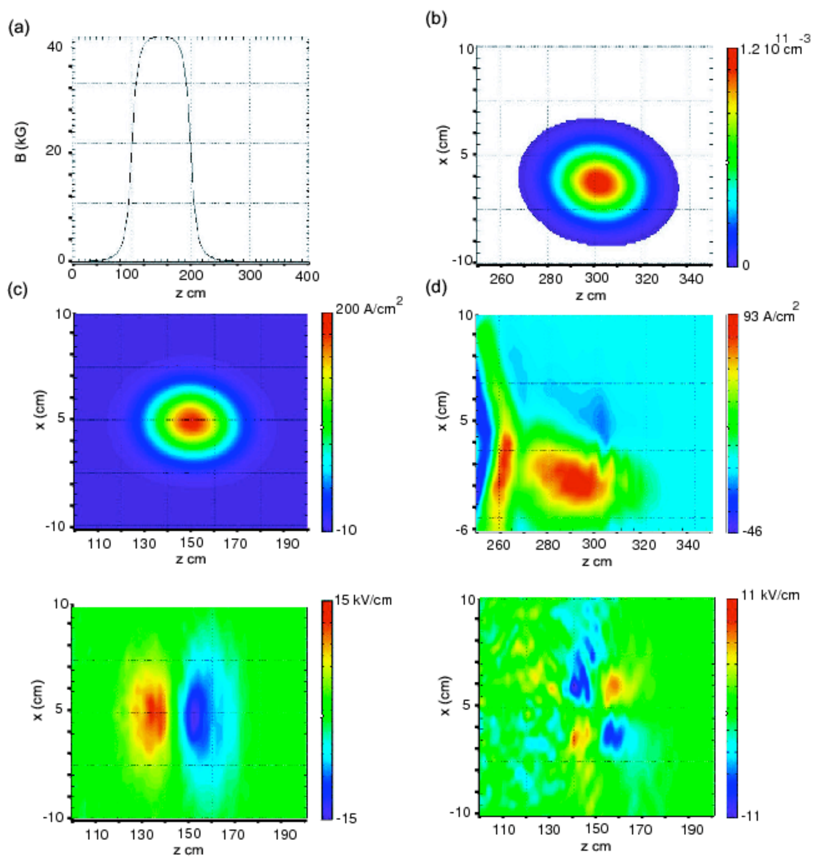

Figure 5. Beam propagation in a dipole magnetic field. Plots correspond to: (a) the magnetic field of the dipole, B_y; (b) the beam density in the dipole region; (c) the current density in the dipole region, j_z; (d) the current density outside the dipole region, j_z; (e) the longitudinal, inductive electric field, E_z; and (f) the transverse electric field, E_x. The beam and plasma parameters are The background plasma density is $n_p=10^{11}cm^{-3}$. The beam velocity is $V_b=0.2c$; the beam current is 1.2kA (48.0A/cm^2), which corresponds to the ion beam density $n_b=0.5n_p$; and the ion beam charge state is $Z_b=1$. The beam dimensions (r_b=2.85cm and τ_b=1.9 ns) correspond to a beam radius $r_b=1.5\,c/\omega_{pe}$, and pulse duration $\tau_b\omega_{pe}=75$.

The possibility of beam steering by utilizing a dipole magnet in background plasma has been studied in large-scale particle-in-cell simulations [I. D. Kaganovich, A. B. Sefkow, E. A. Startsev, and R. C. Davidson, Dale R. Welch, "Effects of finite pulse length, magnetic field, and gas ionization on ion beam pulse neutralization by background plasma", Nuclear Instruments and Methods in Physics Research A **577**, 93 (2007)]. It was shown that, in 2D simulations, the beam is not neutralized due to electron attachment to the magnetic field lines. In 3D simulations, electrons from the background plasma can neutralize the beam space charge by flowing along the magnetic field lines. However, a quadrupole-like structure of the electric field appears due to **vxB** drifts, as shown in Figure 5. The effect of this electric field on the beam emittance has to be yet investigated.

4. Complete implementation and initial tests of large-scale particle simulations of electron-ion two-stream interactions in bunched beams using optimized numerical models, with electron production mechanisms self-consistently included (Completed September, 2008).

The recently developed nonlinear delta-f particle simulation capability for 3D high-intensity bunched beams incorporated in the BEST code has been applied to the study of the electron-ion two-stream instability (so-called electron cloud instability) in bunched ion beams. Due to the complexity of 3D multi-species kinetic equilibria with temperature anisotropy, the background electrons are simulated using the total-f (particle-in-cell) method, and the beam ions are treated by means of the delta-f method. There are two additional advantages of using this algorithm: (1) The electron perturbations typically reach a large amplitude much faster than the ion perturbations because of the large mass ratio. It is therefore prudent to use the total-f method for the electrons in order to reduce the large noise induced by the growing weight associated with the delta-f method. On the other hand, it is desirable to use the delta-f method to simulate the beam ions because the ion perturbations have much smaller amplitude, and the delta-f algorithm can reduce the simulation noise significantly; (2) The total-f approach for the electrons is readily compatible with the secondary electron yield model that has been implemented in the BEST code. Compared with previous studies of the electron-ion two-stream instability for long coasting beams, the simulation results show that finite bunch-length effects have a stabilizing influence. For purposes of illustration, a typical simulation result is shown in Figure 6 for a high-intensity, bunched proton beam passing through a stationary electron background, with relativistic mass factor 1.8 for the protons, and normalized space-charge intensity $s_b = 0.07$. The average fractional charge neutralization provided by the background electron population is taken to be 10% , and the bunch length is 40 times longer than the rms radius of the ion charge bunch in the transverse direction. Previous studies of the electron-ion two-stream instability for long coasting beams, using similar parameters, showed that the two-stream interaction between the beam ions and the background electrons is unstable. Plotted in Figure 6 is the time-history of the perturbed ion density at one spatial location. The beam ion density is initially perturbed by the space-charge force of the background electrons, but there is no measurable two-stream instability associated with the relative streaming motion between the beam ions and the background electrons, leading to an effective readjustment of the equilibrium, even though some collective mode excitations are evident. This is because the bunch length for this choice of system parameters is shorter than the longitudinal wavelength characteristic of the instability for the case of a long coasting beam. Further numerical studies will be carried out in order to provide a more complete parameterization of detailed stability behavior.

The stabilizing effects of finite bunch length have also been observed in recent simulation studies of the two-stream interactions between the highly-relativistic beam electrons and the background protons produced by ionization of background gas atoms, envisioned in the proposed Cornell Energy Recovery Linac (CERL) project. Because the electron beam is highly relativistic, the self-field effects of the beam electrons are negligibly small. The important space-charge effects are primarily due to the interaction between the beam electrons and the background ions through the large space-charge potentials. The BEST delta-f simulations show that for an average fractional charge neutralization of 0.1%, CERL should be stable with respect to the two-stream interaction, because the longitudinal wavelength required for the two-stream instability is much longer than the bunch length. Even if the bunch length is comparable to the wavelength, a moderate momentum spread at the 0.33% level is found to be sufficient to suppress the instability.

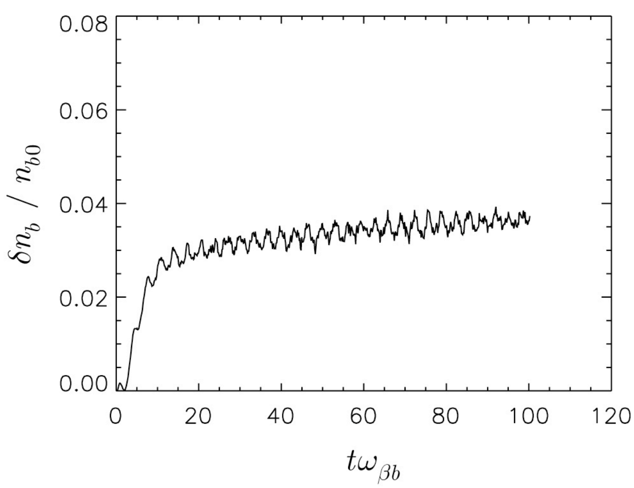

Figure 6. Time-history of the ion density perturbation at one spatial location for a high-intensity, bunched ion beam propagating through a stationary electron background.

A.2 Fusion Execution Agreement Milestone for FY 2008

5. Complete assessment of the effects of the strong temperature anisotropy instability on finite-length bunched beams (Completed June, 2008).

In 3-D high-intensity bunched beams, collective effects with strong coupling between the longitudinal and transverse dynamics are of fundamental importance. A direct consequence of this coupling effect is that the particle dynamics does not conserve transverse energy and longitudinal energy separately, and there exists no exact kinetic equilibrium that has an anisotropic energy in the transverse and longitudinal directions. The strong coupling also introduces a mechanism for the electrostatic Harris-type instability, which is driven by extreme energy anisotropy and exists naturally in intense charged particle beams that have been accelerated. The self-consistent Vlasov-Maxwell equations have been applied to high-intensity bunched beams, and a modified low-noise δf particle simulation algorithm has been developed for bunched beams with or without energy anisotropy [H. Qin, R. C. Davidson and E. A. Startsev, Physical Review Special Topics on Accelerators and Beams **10**, 064201 (2007); H. Qin, R. C. Davidson and E. A. Startsev, Nuclear Instruments and Methods in Physics Research **A577**, 86 (2007)].

Wave-particle resonance between a simulation particle and a coherent mode structure in a 3D bunched beam often results in a large weight growth for that simulation particle, which in turn creates a large local error field in the simulation. To overcome the noise issue brought about by the large weight of nearly-resonant simulation particles, we have developed a modified δf method that can switch smoothly between the δf and total-f methods. Before the switch, the simulation still makes effective use of the low-noise feature of the δf method for small weight to follow the detailed evolution of the unstable mode structures. When the weight function becomes sufficiently large during the nonlinear phase, the low-noise advantage of the δf method is reduced and the simulation is switched to the total-f method to avoid the large noise induced by the nearly-resonant simulation particles. In this modified algorithm, the particle distribution is partitioned as $f = \alpha f_0 + wF$, where every term except for α has the same meaning as for the standard δf method. The new feature here is the coefficient α(t), which is a function of time and takes on continuous values between 0 and 1. The case of α=0 corresponds to the total-f method, and the case of α=1 corresponds to the standard the δf method. The perturbed fields are determined from the perturbed Maxwell equations using the perturbed distribution, which is constructed from α, w, and F as $\delta f = (\alpha - 1) f_0 + wF$. The coefficient α can also be allowed to depend on phase-space coordinates, and the extra freedom associated with α(t) is introduced to achieve the desired numerical advantages [H. Qin, R. C. Davidson and E. A. Startsev, Physics of Plasmas **15**, 063101 (2008)].

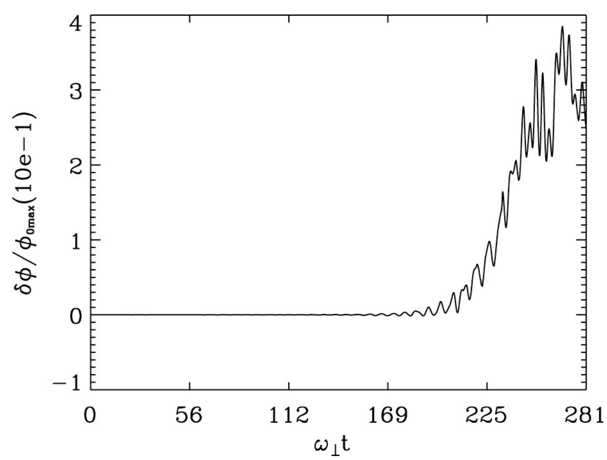

Figure 7. Potential perturbation at one spatial location using the standard δf method for the anisotropy-driven Harris instability. The simulation result is accurate during the unstable linear growth phase before t=140/$\omega_\perp$, but is dominated by large error fields introduced by the noise associated with the large weight for nearly-resonant simulation particles during the nonlinear phase after t=170/$\omega_\perp$.

Shown in Figure 7 is the simulation result for the Harris instability using the standard δf method, from which we observe that the simulation is accurate for the unstable linear growth before $t=140/\omega_\perp$, and valuable information about the instability evolution has been obtained. However, the signal during the nonlinear phase after $t=170/\omega_\perp$ is dominated by the error fields, and the simulation 'crashes' shortly after $t=229/\omega_\perp$. Valid simulation results for both the linear and nonlinear phases have been obtained using the modified δf algorithm with the switch between the standard δf and total-f methods, shown in Figure 8. The smooth switch is automatically triggered when the maximum absolute value of weight for all particles is larger than 1. In this simulation, the switch is triggered at time $t=162/\omega_\perp$. We can clearly identify the well-behaved linear growth and nonlinear saturation dynamics in Figure 8.

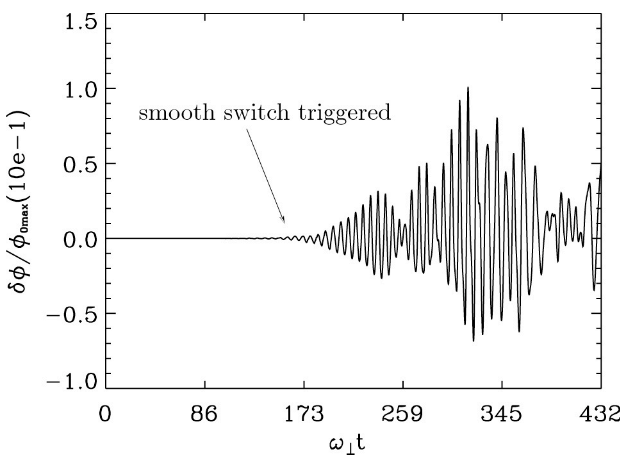

Figure 8. Potential perturbation at one spatial location using the modified δf method with a smooth switch. The smooth switch to the total-f method is automatically triggered when the maximum absolute value of the weight for all particles is larger than 1 at $t=162/\omega_\perp$. The result is valid for both the linear growth and nonlinear saturation dynamics.

B Experimental Activities and Feasibility Studies

B.1 Research Objectives for FY 2008

1. Develop plasma and beam diagnostics for installation on the NDCX beamline to provide between-shot information on plasma properties during beam compression experiments, and to measure the spatially resolved ion current density and pulse duration (Completed April, 2008).

A retractable Langmuir probe has been built to provide between-shot information on the plasma produced by the barium titanate ferroelectric plasma source (FEPS). The probe is designed to rest against the inner wall of the FEPS during NDCX beam experiments so as to not interfere with the NDCX beam propagation. The probe can be rotated about its axial support so that the probe tip moves along an arc away from the inner wall and towards the machine axis. The probe tip moves in a transverse plane located in the 1.75-inch-long grounded interface region between the FEPS sub-sources that comprise the full-length plasma source. The probe is constructed with a length of semi-rigid coaxial wire that has a central conductor diameter of 0.040” and an outer jacket diameter of 0.125”. The wire runs axially along the outer surface of the FEPS and then enters through one of the one-inch-diameter access holes. After passing through the access hole, the wire is curved so that it conforms to the inner surface of the FEPS. The probe is intended to be operated with an approximately 100 V bias in order to collect the ion saturation current since this has proven to be the most useful technique for measuring the plasma density in previous Langmuir probe measurements on the FEPS. This probe will allow the status of the FEPS to be monitored *in-situ* without requiring NDCX to break vacuum.

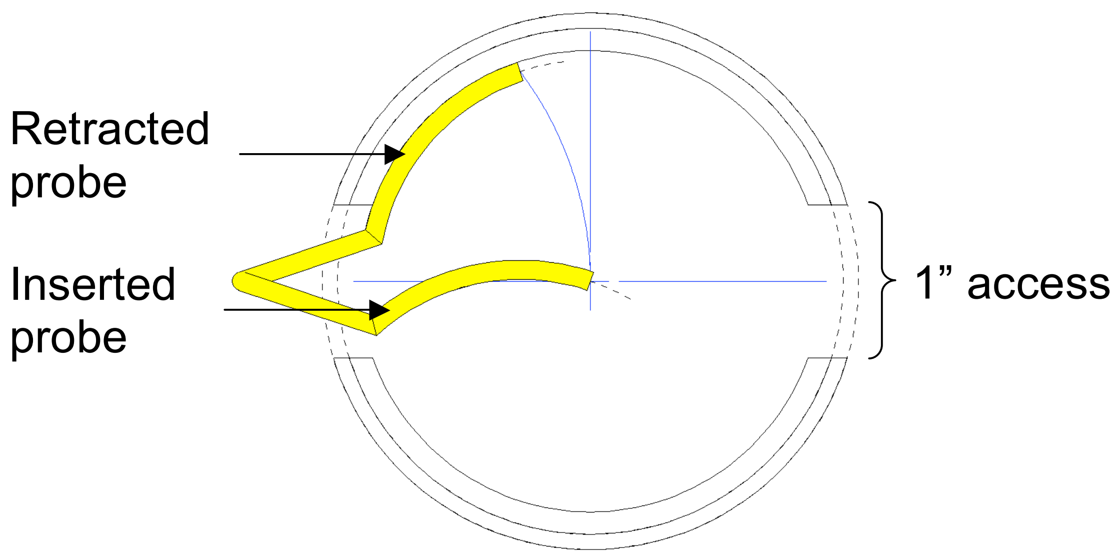

Figure 9. The retractable Langmuir probe (yellow) is designed to rest against the inner wall of the FEPS (retracted probe) when not in use, and it can be rotated into position to make plasma density measurements during NDCX shots when no beam is delivered (inserted probe).

A Rogowski coil has been built to measure the unneutralized NDCX beam current and pulse length as the beam passes through the portion of the drift compression region spanned by the FEPS. A flexible Teflon rod is threaded with a standard #8-32 die and then wound with copper wire to create a coil that fits within the 3.010” inner diameter of the interface region between the FEPS subsources. The coil has 289 loops, each with an area of 9.2 mm^2. For typical NDCX parameters such as I_{beam} = 25 mA and ~ 100 ns rise-time, the expected signal is several milliVolts. In order to reliably measure such small signals, various techniques are under consideration for reducing capacitive pick-up noise. These techniques include double-coil configurations where the capacitive pick-up signal can be eliminated by subtraction, and also standard shielding methods.

B.2 Fusion Execution Agreement Milestone for FY 2008

2. Determine the feasibility of experiments using present facilities and their upgrades to study warm-dense- matter ion-ion plasmas produced from halogen foil targets heated by intense ion beams depositing energy near the dE/dX peak (Completed September, 2008).

With the presently available pulse compression capabilities of the Neutralized Drift Compression Experiment (NDCX), it appears that temperatures of about 0.1 eV may be obtainable. This is near the lower boundary of what may be required for very weakly ionized ion-ion plasmas in halogen foil targets. If planned improvements that would allow simultaneous longitudinal compression of the beam by the factor of 170 that has already been achieved, along with transverse compression to about 1 mm radius can be realized, then it should be possible to heat the foils to 0.4 - 1.0 eV, which would be enough to allow ion - ion plasma studies in the warm dense matter (WDM) regime using halogen foils. We have recently realized that a layer of a halogen salt, such as sodium chloride, evaporated on a substrate, may form an interesting target for testing the experimental setup before dealing with the issues of fabricating, storing, and handling foils of iodine or bromine. Further exploration of the concept of using a salt target has led to the preliminary conclusion that potassium chloride might be a better initial target, since potassium and chlorine have almost the same average mass, and we would like the charge carriers to be as mass-symmetric as possible. The simplest way to fabricate a potassium chloride target would be to evaporate a drop in a distilled water solution onto a backing of either gold or carbon. Surface tension would likely result in non-uniformity of deposition at the edge of the drop, but the center would likely be relatively uniform.

We have recognized from the onset that the most challenging aspect of the ion – ion plasma experiments using foils as targets will be to find ways of measuring properties of the very transient ion – ion plasma when it is likely to be surrounded by electron – ion plasmas. Thus, it would be of great help if we link these experiments, when they are carried out, to renewed studies of halogen ion – ion plasmas in ion sources, where we began this work. These plasmas are much easier to study using the diagnostic technique we pioneered, which uses the extracted beams as a window into the plasma conditions. The manuscript for an invited paper describing the research on ion – ion plasmas in halogens has been accepted for publication [L.R. Grisham, "Negative Halogen Ion Sources", IEEE Transactions on Plasma Science, in press (2008)]. As an outgrowth of our studies of beam extraction from chlorine ion – ion plasmas, the concept of halogen-enhanced extraction of D^- beams from deuterium ion sources used for heating and current drive in tokamaks has recently been proposed, which is described in a paper prepared for the 2008 *Symposium on Heavy Ion Fusion* to take place in Tokyo in August, 2008 [L. R. Grisham and J. W. Kwan, "Perspective on the Role of Negative Ions and Ion – Ion Plasmas in Heavy Ion Fusion Science, Magnetic Fusion Energy, and Related Fields," Nuclear Instruments and Methods in Physics Research, submitted for publication (2008)].

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